Universal Interconnection Technology Workshop

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Introduction

It is important to understand *why* we are want Distributed Energy Resources (DER), so that we can best establish *how* to implement them.

In 1973, E.F.Schumacher said in his classic book, *Small is Beautiful*:

> We need methods and equipment which are:
> - Cheap enough so that they are accessible to virtually everyone;
> - Suitable for small scale application; and
> - Compatible with man's need for creativity

Small is Beautiful is the underlying philosophy behind Distributed Energy Resources. Thirty years later, however, there are additional reasons for adopting this technology.

The foremost of these now is security – which may be divided in to three areas - power reliability, power quality and immunity from attack. The National Research Council in a recent report to Congress and the Department of Homeland Security has recommended that we "Develop, test and implement an intelligent, adaptive electric-power grid":

> Recommendation 16: Technology should be developed for an intelligent, adaptive power grid that combines a threat-warning system with a distributed-intelligent-agent system. This grid would be able to rapidly respond with graceful system failure and rapid power recovery. It would make use of adaptive islanding—a concept employing fast-acting sensors and controls to "island" parts of the grid as the rest comes down—and technologies such as storage units positioned at key points to minimize damage during shutdown. The system would need to be able to differentiate between a single component failure and the kind of concurrent or closely coupled serial failures at several key nodes that would indicate the onset of a concerted attack.

The following was reported in the LA Times, and on CBS News:

> --1 July 2002 Attacks on Power Companies Growing
> Power companies are increasingly being targeted by hackers, according to data gathered by RipTech. FBI spokespersons expressed concern.

Another reason is the environment. We know that atmospheric pollution from power plants is contributing to global warming. New technologies such as fuel cells offer much cleaner ways to generate electricity. Schumacher said:

> Small scale operations, no matter how numerous, are always less likely to be harmful to the natural environment than large-scale ones, simply because their individual force is small in relation to the recuperative forces of nature.

Further, we are using our natural capital (i.e., coal and oil) instead of changing to sustainable energy systems. Again, from *Small is Beautiful*:

> It is clear that the "rich" are in the process of stripping the world of its once-for-all endowment of relatively cheap and simple fuels.

Distributed Energy Resources also promise lower energy costs by having lower initial design costs, shorter time to market, standardized components, higher efficiencies (which still need to be demonstrated for most technologies), heat recovery (also known as Combined Heat and Power, or CHP), storage (for Distributed Energy Storage devices) and lower distribution losses (as electricity is generated near its place of use).

The main impediments to the wide-scale implementation of DER have been cost, immature technology, and safety concerns – will a DER device energize a section of the grid (i.e., form an island), will it damage utility or consumer equipment, can it disrupt power quality or reliability?

In summary, to make Distributed Energy Resources fully viable, we need to make these devices:

- Secure (providing reliable, high quality power and immunity from attack)
- Flexible (capable of feeding the grid and operating in intentional islands)
- Efficient and Cost-effective
- Renewable and Sustainable
- Safe

Interconnection Technology

In the technology area, many issues have been solved:

- IEEE 1547 will become a national standard for characteristics such as voltage and frequency trip setpoints and islanding performance
- Current-controlled inverters are well understood – the quality of the power generated by DER systems is satisfactory.
- Adequate anti-island techniques have been developed.

Other issues are still open:

- Multi-inverter islanding has not been addressed.
- Methods of controlling microgrid and intentional islands need to be developed and standardized.

- Well defined procedures are needed for testing to minimize time to market and costs, and to ensure reliable results.
- The possibility of DC being fed onto the grid needs to be addressed.
- There is a need to certify controllers, control schemes and controller code rather than individual inverter models (we believe that this is a key to universal interconnection).

Finally, there are myths that need to be dispelled, for example:

- Voltage and frequency protective relaying alone can provide reliable anti-islanding protection. Protective relays are still considered acceptable by many utilities.
- UL1741 island tests are sufficient to ensure multi-inverter protection
- Induction generators cannot island.
- Islanding is unlikely to occur. This is true for properly designed inverters – but islanding is actually very likely to occur if anti-islanding schemes are not implemented well.
- Line workers are endangered by islanding. Standard procedures, which are carefully followed, require disconnection, test and grounding of equipment before any work starts.

Islanding

The basic theories of island prevention are now well understood. We believe that the problem is essentially solved.

Advanced Energy introduced the ideas that now are accepted as best practice in the USA (real and reactive power feedback schemes), and has been granted a broad patent on these concepts. The Patent covers feedback and acceleration methods which are also known as the Sandia Voltage and Sandia Frequency Shift techniques (SVS & SFS).

There is still however work to be done: we need to prove the viability of island prevention techniques at high penetration levels, we need to model stability in the wide-area grid as penetration increases and we need to model and test multi-inverter systems and various methods operating together.

There is also a need for standardized test methods that clearly identify test setups and procedures. An example of this is the current question as to whether Sandia's test equipment (with iron cored inductors) differs significantly from UL's test setup (with more linear, but higher loss air-cored inductors). Finally, there is a question as to whether we should test with rotating machine loads, even though there is strong evidence that induction motors will not support islands any more than an equivalent compensated RLC circuit.

Anti-Islanding Primer

The following is a brief summary of the various methods that are used for island prevention.

Passive Trips (Voltage and Frequency)

If the grid voltage or frequency goes outside set limits, the inverter stops exporting. This is sufficient to prevent islands where there is real or reactive load mismatch. As the load will respond to Ohm's Law (voltage = current x impedance), the allowable limits translate directly to the possible islanding load range.

Phase Jump Detection

Phase Jump Detection causes a shutdown if a sudden change in phase of the grid voltage waveform is seen. It was used successfully in early U.S. inverters such as the APC Sunsine. It suffers from two problems – sudden voltage phase changes can occur on a normal grid if low power factor loads such as induction motors come on line (leading to false trips), and a well matched load will not create a phase jump upon loss of grid (leading to a non-detect zone).

Harmonic Monitoring

This technique was popular for a while, but relying on either ambient grid harmonics or high frequency signals generated by the inverter is subject to wide variability, especially if other noise sources or harmonic traps such as power factor correcting capacitors are present.

Impedance Measurement/Power Shifting

Impedance measurement and power shifting are essentially the same – if we change the output current and observe the resulting voltage change, we are measuring impedance. The problem with simple impedance measurement is that if multiple inverters are used, and the power shifts are not synchronized then the voltage change in response to a current change will be diluted by the number of inverters on-line. If they are synchronized then flicker problems are likely. It is generally accepted that simple power shifting techniques are not adequate in multi-inverter installations. The German ENS system is an impedance measurement system.

Frequency Bias

These methods generate a current waveform that is slightly higher or slightly lower in frequency than the observed voltage waveform frequency. They fail at high Q's where the frequency bias is overcome by the load phase characteristic and also require a decision as to whether to always go up, or to go down (which may be conflicting in a multi-inverter situation).

Real Power Feedback

This method responds to small changes in grid voltage by making a change in output current that would result in an even bigger change in voltage, should an island exist. This is also known as the Sandia Voltage Shift (SVS) method. After a few cycles, the inverter stops with an upper or lower voltage trip. When carefully implemented, this technique can provide reliable island protection in both the single and multi-inverter cases.

Reactive Power Feedback

Reactive power feedback is similar to real power feedback – the reactive power output of the inverter (or phase or shape of the output current waveform) is changed in response to an observed change in the operating frequency of the inverter. As the inverter load in an island situation can be modeled as a parallel RLC circuit, changing the inverter's reactive power output is the same as adding inductance or capacitance to the RLC tuned circuit, and thus changing its resonant frequency. After a few cycles, the inverter stops with an upper or lower frequency trip. This technique is also known as the Sandia Frequency Shift (SFS) method. It can be combined with the real power feedback method and will provide reliable island protection in both the single and multi-inverter cases.

Direction & Acceleration

Two other concepts were introduced in our patent: First, the direction of the power or frequency response should be in the same direction as the observed change on the grid (and so in the same direction as other inverters). This overcomes the problem of deciding whether to bias up or down in frequency or power. We call this *following the herd*. The second concept is *acceleration* – if the voltage or frequency continues to change in the same direction, the magnitude of the response is increased exponentially each time. This results in faster trip times, lower initial response values and undetectable flicker levels.

Islanding - Known Problems

Non-detect Zones

Professor Michael Ropp's work in modeling frequency bias schemes showed that these, and most other non-feedback techniques, suffer from Non-Detect Zones (NDZ) in the load impedance plane. For example, power shifting will not detect inside the allowable grid voltage limits, and frequency bias will not detect if the load Q exceeds the slope of the inverter phase/frequency characteristic. Recently, we have discovered other non-detect areas related to thresholds, and measurement and output resolution.

Flicker

Any method that causes changes in inverter output power may result in flicker problems. The change in output must be carefully balanced with respect to flicker and anti-island sensitivity. The voltage and frequency feedback methods do not have flicker problems if acceleration is used – typical output current variations are of the order of 0.5%, which is the output control resolution of the inverter.

Dilution of power shifting methods

This is discussed above - the voltage change in response to a current change will be diluted by the number of inverters on-line

Thresholds

Some island protection techniques rely on a measured value exceeding a fixed threshold to initiate a power or frequency change. This can lead to non-detection if the noise level in the island is lower than the threshold. Techniques that rely on fixed thresholds are best avoided.

Measurement Resolution

Another non-detect problem can come from quantization of input measurements. For example, a voltage feedback scheme that measures grid voltage with 1 Volt rms resolution may not see any changes in voltage once an island occurs, and will not initiate power output changes.

Output Quantization

If a 1 kW inverter can only control its output in 5% steps, and a 1% change in input voltage is seen, the required output change may be calculated as 2% which is less than the output step size – power feedback will only start if a voltage change of 2.5% is seen. This is another form of threshold NDZ.

Incompatibility of Different Methods

The largest unknown in islanding is how different methods will interact. For example, how will a voltage feedback scheme work with a power-shifting scheme? Much depends on the number and size of inverters of each type.

Some combinations are clearly incompatible – a frequency-shifting scheme that pushes up combined with an inverter (or perhaps a motor load) that is pulling down, for example.

Islanding Conclusions

We believe that our real and reactive power feedback methods are presently the best possible techniques for island prevention.

Because of the potential for incompatibility between different methods, we believe that a standard anti-islanding method, not a performance test, should be adopted. A standard method would also lend itself to certified inverter controllers.

Finally, we must base future work on theory, not on experimentation. We should use understanding and accurate computer models to establish the viability and reliability of our islanding protection schemes.

DC Injection

Many inverter designs can inject DC onto the line. For example, a half-bridge inverter such as the older Omnion design with a shorted IGBT (and probably also a control system failure that allows the AC contactor to close) could connect 400V DC from a PV array directly to a 120V distribution line. There may be industrial or commercial equipment that could create the same hazard on multi-phase systems – for example, rectifiers, motor drives and welders. Incorrect installation could create this hazard even with a transformer-isolated inverter if a DC input wire came loose and shorted to the output.

High voltage DC could be very hazardous to a line worker who is only equipped with AC measuring equipment. Because of this, there is an urgent need to alter utility test procedures. A compensating factor is that this problem could only occur at the level at which the inverter is connected (typically the distribution transformer secondary), and so precautions would not be needed at the medium voltage distribution level.

Some utilities are questioning non-transformer-isolated designs, but this is more from a concern of saturating distribution transformers than of creating a safety hazard. There is a need to distinguish between high frequency isolation transformers in DC-link inverters (that still have high voltage DC outputs) and low frequency isolation transformers.

We need to establish minimum monitoring and protection requirements (such as checking for DC voltage components on the inverter output) for inverters that do not use low-frequency transformers.

Microgrids and Intentional Islands

The National Research Council recommended that we develop an intelligent, adaptive electric-power grid. This means that DER devices will not only need to export power to the normal grid – they must also be able to support an intentional island.

We need to agree on how devices will work together via communications and their electrical interface. We must allow for steady state, transient and fault conditions, and also for non-unity power factor and high harmonic loads.

We must also develop schemes for dispatching devices both in minigrid and normal grid-connected modes. For example, in a minigrid, we should run just enough generation to satisfy the load, and recharge energy storage.

AEI has been working on these and related problems for three years with the Sandia Energy Storage group.

Certified Controllers

Presently, the cost of listing an inverter with Underwriter's Laboratories is very high, and is increasing (it is typically \$50 to \$100K per inverter). Much of this testing is to verify the anti-islanding performance of the inverter. Tests are required at 25, 50 and 100% of inverter rating with high Q RLC matched load (100% resistive, 250% inductive and capacitive).

This testing could be eliminated if the anti-islanding method was completely understood and if the behavior of the inverter controller was fully tested and certified.

From both the manufacturer's and the utility's point of view, it would be far preferable to have one certified controller than ten different inverter models.

The functions tested in a certified controller would include:

- Under and over voltage and frequency trips
- Active anti-islanding scheme
- Power quality (to be re-tested on each inverter version)
- Intentional-island support mode
- Mode transitions
- Safety shutdown behavior
- Watchdog functionality
- Non-volatile setpoints
- Calibration accuracy and reliability
- Dual redundant grid voltage sensing
- Communications protocol compliance.

We believe that this is a major step on the path to universal interconnection technology.

Communications

DER communications are required for performance monitoring, remote diagnostics, and control/dispatch functions. Even though a well-designed DER system should be able to operate autonomously, remote communication is necessary to allow the full benefit of DER (especially dispatch based on real-time pricing) and to minimize field service costs.

The IEEE recently approved the formation of a working group for P1614, *Draft Guide for Monitoring, Information Exchange and Control of Distributed Resources Interconnected with Electric Power Systems.* This working group will be the focus for DER communications work.

Key areas in this work are:

- Protocol definitions (it is likely that multiple protocols will be supported including existing utility SCADA protocols). An XML protocol is also likely to be supported.
- Object Models (data description models for inverters and generation and storage devices).
- Security (data encryption standards, key management, authentication).
- Threat analysis and warning (as identified in the National Research Council report).

As communications controllers must be very low cost, especially for the smaller DER systems, an important area that requires development is encrypted protocols that are adequate, but simple enough to be implemented on low-end microprocessors. Software to implement standard internet (TCP/IP) communications on low-cost microprocessors is readily available, but cryptographic security protocols such as the Secure Sockets Layer (SSL) are presently not.

Conclusions

The key areas that we have identified for research towards a Universal Interconnection Technology are:

- A standard anti-islanding method that is proven in the multi-inverter case
- Control schemes for microgrids and intentional islands
- Certified controllers
- Test procedures
- Communications protocols and object models
- Cryptographic techniques such as SSL for use in micro-controller-based DER communications devices.

There is a wisdom in smallness if only on account of the smallness and patchiness of human knowledge, which relies on experiment far more than on understanding.
(E.F. Schumacher)